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Scaling Effects in the Static Large Deflection Response of Graphite-Epoxy Composite Beams

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SCALING EFFECTS IN THE STATIC LARGE DEFLECTION RESPONSE OF GRAPHITE-EPOXY COMPOSITE BEAMS

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ABSTRACT

Scaling effects in the large deflection response of graphite-epoxy composite beams was investigated. Eight different scale model beams ranging from 1/6 to full scale were subjected to an eccentric axial compressive load to promote large bending deformations and failures. Beams having laminate stacking sequences including unidirectional, angle ply, cross ply, and quasi-isotropic were tested to examine a wide variety of composite response and failure modes. The model beams were loaded under scaled test conditions until catastrophic failure. Data acquired included load, end displacement, and strain measurements, and qualitative failure measurements. The experimental data is compared to a large rotation beam analysis and a finite element model analysis. Results from the tests indicate that the beam response scales in the small deflection region, but deviates as the response becomes nonlinear. Failure modes are consistent between scale models within a laminate family, however, a significant scale effect is observed in strength of the scaled beams. Small scale beams fail at higher normalized load and significantly higher normalized end displacement levels than their full scale prototypes. It is important that this phenomenon be understood before strength testing of scale model composite structures can be utilized.

INTRODUCTION

Scale model technology represents one method of investigating the structural crashworthiness of advanced, weight efficient composite aircraft components such as beams, frames, and rings. Impact tests on replica models of composite structures can provide a cost effective alternative to full-scale crash tests. In addition, scale model tests can be conducted to verify analysis techniques, particularly finite element analyses. It is important, however, to understand the limitations of scale modeling so that tests on sub-scale models will generate valid data. Scaling effects in the response and failure of composite structures must be characterized before the technique can be used to full advantage. A series of tests were conducted by Morton [1] to examine scaling effects in the dynamic response of transversely impacted composite beams. Results from those tests indicated that classical scaling laws apply for elastic dynamic response, but a size effect was observed as the beams became damaged under greater impact loads.

The objective of the current research is to investigate scaling effects in the static large deflection response of composite beams. The scaled beams are loaded in a beam-column fashion by an eccentric axial compressive load. This testing configuration produces large bending deformations and promotes global failure of the beams away from the supported ends. A dimensional analysis was performed on the beam-column system using methods outlined in Baker [2] to determine the non-dimensional parameters or Pi terms which govern the scaled response. An experimental program designed to validate the scaling laws was performed and initial results are reported in this paper. Also, a one dimensional large rotation analysis and a DYnamic Crash Analysis of STructures (DYCAST) [3] finite element model of the composite beam were developed for comparison with experimental results. The results obtained from the static experiments along with a verified DYCAST model will be used to develop a test matrix for conducting impact tests and dynamic analyses in the future.

EXPERIMENTAL PROGRAM

Beams having unidirectional, angle ply, cross ply, and quasi-isotropic laminate stacking sequences were constructed of a high modulus graphite fiber and an epoxy matrix system designated as AS4/3502* for the static tests. The full scale beam was 3 inches wide with a 30 inch gage length and 48 plies thick with an average ply thickness of 0.0054 inches. The scale model beams were constructed by applying seven different geometric scale factors including 1/6, 1/4, 1/3, 1/2, 2/3, 3/4, and 5/6, to the full scale beam dimensions. A set of scaled beams is illustrated in Figure 1 and the dimensions and lay-ups of each beam are listed in Table 1. The thickness dimension was scaled by reducing the number of layers in each angular ply group of the full scale laminate stacking sequence which consisted of at least six plies of similar orientation. Using this approach, it was not possible to fabricate a 1/4 or 3/4 scale quasi-isotropic beam. Three replicate tests were conducted for each laminate type and size of beam. The beams were machined from panels which were constructed by hand from pre-preg tape and cured according to manufacturer's specifications. Slight variations were observed in the thickness dimensions of the cured beam specimens. Generally, the 1/6 scale beam was thicker on a per ply basis than the full scale beam for all laminate types. The maximum deviation in normalized thickness was approximately six per cent.

During the tests each beam specimen was gripped in a set of hinges which offset the axial load with a moderate eccentricity, as shown in Figure 2. Eight sets of hinges were constructed to ensure that the

*Identification of commercial products and companies in this paper is used to describe adequately the test materials. The identification of these commercial products does not constitute endorsement, expressed or implied, of such products by the U.S. Army, the National Aeronautics and Space Administration, or the publishers of these conference proceedings.

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end condition was properly scaled for each test. The hinges were pinned to the platens of a standard load test machine which applied the compressive vertical load. The hinged-pinned connection allowed the beam to undergo large rotations during deformation. Beam specimens were loaded until catastrophic failure, defined as loss of load carrying capability.

Each beam was instrumented with back-to-back strain gages located at distances one-quarter and two-thirds along the length and with strain gage rosettes at the midpoint. Vertical load was measured by a load cell located at the base of the bottom hinge. End displacement was measured by an extensiometer attached to the platens of the load test machine. Vertical load, end displacement, and strain data were recorded using a personal computer based data acquisition system. The analog signals were amplified and filtered prior to being digitized and converted to engineering units. Only the load versus end displacement data will be presented in this paper.

ANALYSIS

A one dimensional large rotation "elastica" type solution was developed to predict the response of the composite beam-column under eccentric axial load. The governing equation for the beam was derived from equilibrium of the forces and moments on a beam element. The exact expression relating moment and curvature was incorporated in the analysis, thus allowing the solution to predict large rotation response. The solution of the governing equation is outlined in Timoshenko and Gere [4] for the "elastica" problem and was adapted for this problem by applying the end moment boundary conditions produced by the eccentric vertical load. The solution is given in terms of elliptic integrals and predicts the end displacement, transverse displacement of the midpoint of the beam, and end rotation for increasing load.

The beam bending stiffness was derived from the method described by Whitney [5] in which the bending stiffness, EI, from classical beam theory is replaced by an equivalent stiffness for the composite beam. The beam is considered as a special case of a laminated plate in which the length is much larger than the width. Consequently, the transverse displacement is assumed to be a function of the axial coordinate only. Also, only the moment along the axial direction is assumed to be present. This is analogous to a plane stress assumption in elasticity. The transverse and twist curvatures are expressed in terms of the axial curvature and the bending stiffnesses, and are then substituted into the equation relating bending moment and axial curvature. The equivalent beam bending stiffness is the coefficient of the axial curvature from this equation. It incorporates the shear and twist coupling terms which are important for angle ply and quasi-isotropic laminates.

In addition to the beam analysis, the nonlinear finite element structural analysis computer program DYCAST [3] was used to model the composite beam-column. Since the DYCAST program will be used to model the beam-column under impact conditions in the future, the static case was developed to verify the model and to compare with the large rotation beam solution. The composite laminate was discretized into 60 beam elements which were constrained to permit only planar deformations, as shown in Figure 2. The hinges at the top and bottom of the beam were modeled by two rigid beam elements each. The model assumed pinned conditions between the load machine and the hinge, and clamped conditions between the hinge and beam. The bending stiffness used in the DYCAST model was the same as used in the beam analysis outlined previously. The complete model had 192 degrees of freedom. The applied load was increased incrementally at one end using a static full Newton iterative technique in which the stiffness matrix was updated in each iteration. The full Newton procedure was required since the modified Newton method which updated the stiffness matrix for each load step failed to converge in the nonlinear region of the response curve.

RESULTS

Normalized load versus end displacement plots and corresponding photographs of a complete (1/6 through full scale) set of failed beam specimens for the unidirectional, angle ply, cross ply, and quasi-isotropic laminates are shown in Figures 3-6. Vertical load was normalized by the Euler column buckling load for the beam, and end displacement was normalized by the gage length. Since three repeat tests were performed for each laminate type and size of beam, the results from one representative test are presented here. Repeatability between the three tests was good.

Normalized Load Versus End Displacement Results

In general, the load versus displacement curves show that the response scales for small end displacement ratios, typically less than 0.1. Deviation from scaled response is observed for all laminate types as the beams undergo large deflections and the response becomes nonlinear. The angle ply beams show the most pronounced deviation from scaled response, as seen in Figure 4(a). The small scale beams fail at a higher normalized load and end displacement level than the full scale beam. This observed scale effect in failure behavior is significant. The 1/6 scale beams fail at an end displacement to length ratio from 2 to 10 times the value for the full scale beam depending on the laminate type.

Failure Mechanisms

The photographs shown in Figures 3(b) through 6(b) indicate that while the failure modes for the laminate types considered in this study are different from each other, they are similar between scaled beams within the laminate family. Failure modes appear to be independent of specimen size. The unidirectional beams, shown in Figure 3(b), failed by fiber fractures near the midpoint of the beam. This failure mode is typical of all the unidirectional beams 1/6 through full scale. Failure of the angle ply beams occurred by transverse matrix cracking along 45 degree fiber lines. There was no evidence of fiber breakage, as shown in Figure 4(b). The cross ply laminates exhibited combined failure mechanisms of transverse matrix cracking and fiber fracture. As the cross ply beam underwent large rotations, the 90 degree plies located in the center of the laminate developed transverse matrix cracks. The cracks were evenly spaced and resulted in uniform pieces of debris, some of which are shown in Figure 5(b) for the 5/6 scale beam. The ultimate failure of the cross ply beam was caused by fiber fractures in the 0 degree plies. The quasi-isotropic beams failed through a combination of matrix cracking, delamination, and some fiber failure. Although the photograph in Figure 6(b) does not give a good indication, the damaged quasi-isotropic beams are highly curved. The sequence of failure events occurred such that the remaining intact section of the beam consisted of an unsymmetric laminate, resulting in the observed curvature.

Analytical Results

Comparison of the experimental data for the 1/6 and full scale specimens with the large rotation beam analysis and the DYCAST finite element analysis is plotted in Figures 7(a) through 7(d) for each of the laminate types. Agreement between the two analysis methods is excellent, even though they approach the problem in different manners. The beam solution assumes an inextensible beam, while the DYCAST model allows in-plane deformations due to membrane loads. Also, the large rotation beam analysis incorporates the exact nonlinear expression for beam curvature, while the DYCAST model uses the linear expression. However, these factors do not appear to be important in the response prediction. DYCAST appears to be sufficiently accurate for future dynamic analyses of the scaled beam since a closed form "elastica" type analysis is not available.

Good correlation is obtained between the experiment and the beam solution and DYCAST for small load ratios, generally less than 0.4. However, both the large rotation beam solution and the DYCAST model typically overpredict the experimental beam response as the load ratio and normalized end displacement values increase and beam rotations become large. This is true for all of the laminates tested. The slope of the response curve in the large deflection region (normalized end displacement greater than 0.2) as predicted by both analyses is in good agreement with experiment, as shown in Figures 7(a), 7(c), and 7(d). Overprediction of the response by the large rotation beam analysis and DYCAST may be due in part to certain assumptions made in the analysis including constant stiffness assumptions. The stiffness of the beam is reduced due to nonlinear material properties and damage events such as transverse matrix cracking which are not modeled by the analysis.

DISCUSSION

The results presented here indicate that a significant scale effect exists in the failure behavior since the smaller scale beams fail at a higher normalized load and much higher normalized end displacement value than the full scale beam. Stress and strain based failure criterion such as maximum stress, maximum strain, Tsai-Hill, or Tsai-Wu, would not be able to predict the observed scale effect. According to classical scaling laws, stress and strain should scale as unity. Consequently, under perfectly scaled experimental test conditions the stress and strain in a model beam will be the same as for the prototype. A stress analysis of the scaled test will predict one value of end displacement to length ratio at which failure should occur. Morton [1] discusses a linear elastic fracture mechanics approach to the strength scaling of transversely impacted composite beams and shows that a theory for a notch-sensitive or brittle material can predict scaling effects in a cracked plate. Application of these theories to a stress analysis of the beam-column problem is planned as a continuation of the experimental and analytical results presented here.

CONCLUDING REMARKS

Scaling effects in the large deflection response and failure behavior of graphite-epoxy composite beams was investigated. A series of static tests on scale model composite beams having unidirectional, angle ply, cross ply, and quasi-isotropic laminate stacking sequences was conducted. The beams were loaded under an eccentric axial compressive load to promote large bending deformations and global failure. Plots of normalized load versus end displacement were generated to compare with a one dimensional large rotation composite beam analysis and a DYCAST finite element model.

Results from the experiments show that beam response scales in the small deflection, elastic region; however, deviations from scaled response appear as the beams undergo large deflections and rotations. The degree of variation from scaled response is dependent on laminate stacking sequence. Angle ply laminates exhibited the greatest deviation from scaled response. A significant scale effect in strength behavior was observed even though failure modes were consistent between scale model beams and the prototype within the same laminate family. The one dimensional large rotation beam analysis and DYCAST finite element model gave good agreement with the experimental data for low load ratios, typically less than 0.4. The DYCAST analysis and the large rotation beam analysis overpredicted the beam response in the large deflection region compared with the experiment, but predicted the shape of the response curve well.

The results of this study indicate that an important scale effect exists in the modeling of failure behavior of composite structures. Further work is required to identify the micromechanical mechanisms involved in this effect and to understand how they interact on a macroscopic level to produce the observed scale effect in ultimate failure of the structure.

REFERENCES

1. Morton, John., "Scaling of Impact Loaded Carbon Fiber Composites," Proceedings of the 28th SDM Conference, Part 1., Monterey, CA., April 1987, pp. 819-826.

2. Baker, W.E., Westine, P.S., and Dodge, F.T., Similarity Methods in Engineering Dynamics, Hayden Book Co., Rochelle Park, N.J., 1973.

3. Pifko, A. B., Winter, R., and Ogilvie, P., "DYCAST - A Finite Element Program for the Crash Analysis of Structures," NASA Contractor Report 4040, January 1987.

4. Timoshenko, S., and Gere, J., Theory of Elastic Stability, 2nd edition, McGraw-Hill, New York, 1961, pp. 76-82.

5. Whitney, J., Structural Analysis of Laminated Anisotropic Plates, Technomic Publishing Co., Lancaster, 1987, pp. 68-74.

Table 1. Scale model beam test specimen dimensions and lay-ups.

SCALE	BEAM DIMENSION	UNIDIRECTIONAL	ANGLE PLY	CROSS PLY	QUASI-ISOTROPIC
1/6	0.5" X 5.0"	$[0]_{8T}$	$[45_2/-45_2]_S$	$[0_2/90_2]_S$	$[-45/0/45/90]_S$
1/4	0.75" X 7.5"	$[0]_{12T}$	$[45_3/-45_3]_S$	$[0_3/90_3]_S$	-------------
1/3	1.0" X 10.0"	$[0]_{16T}$	$[45_4/-45_4]_S$	$[0_4/90_4]_S$	$[-45_2/0_2/45_2/90_2]_S$
1/2	1.5" X 15.0"	$[0]_{24T}$	$[45_6/-45_6]_S$	$[0_6/90_6]_S$	$[-45_3/0_3/45_3/90_3]_S$
2/3	2.0" X 20.0"	$[0]_{32T}$	$[45_8/-45_8]_S$	$[0_8/90_8]_S$	$[-45_4/0_4/45_4/90_4]_S$
3/4	2.25" X 22.5"	$[0]_{36T}$	$[45_9/-45_9]_S$	$[0_9/90_9]_S$	-------------
5/6	2.5" X 25.0"	$[0]_{40T}$	$[45_{10}/-45_{10}]_S$	$[0_{10}/90_{10}]_S$	$[-45_5/0_5/-45_5/90_5]_S$
6/6	3.0" X 30.0"	$[0]_{48T}$	$[45_{12}/-45_{12}]_S$	$[0_{12}/90_{12}]_S$	$[-45_6/0_6/-45_6/90_6]_S$

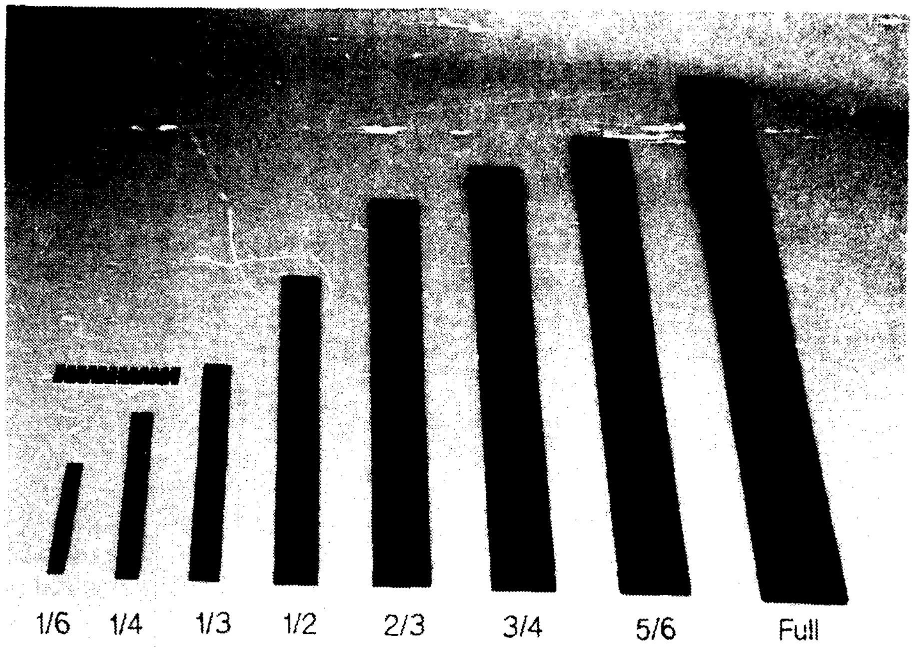


Figure 1. Photograph of scaled composite beam specimens.

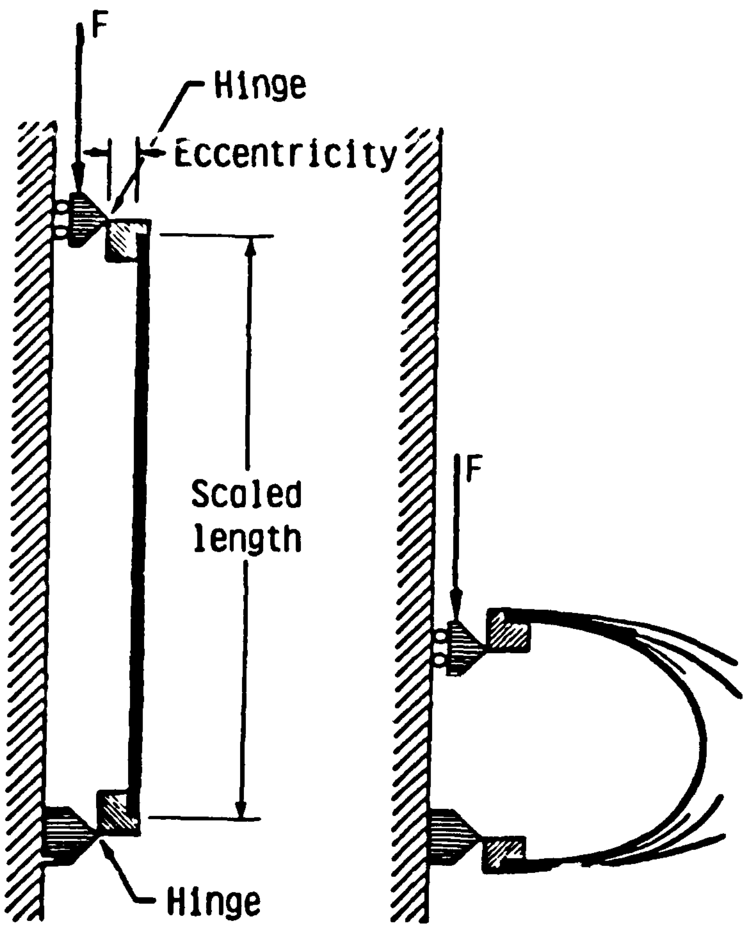
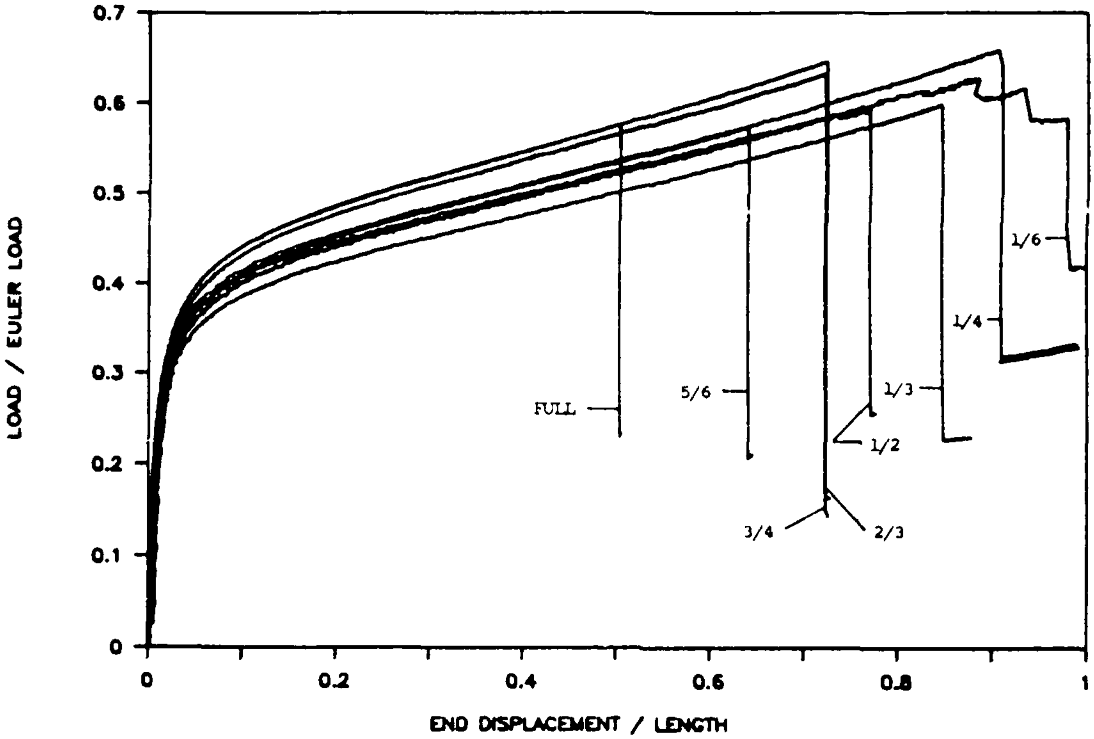
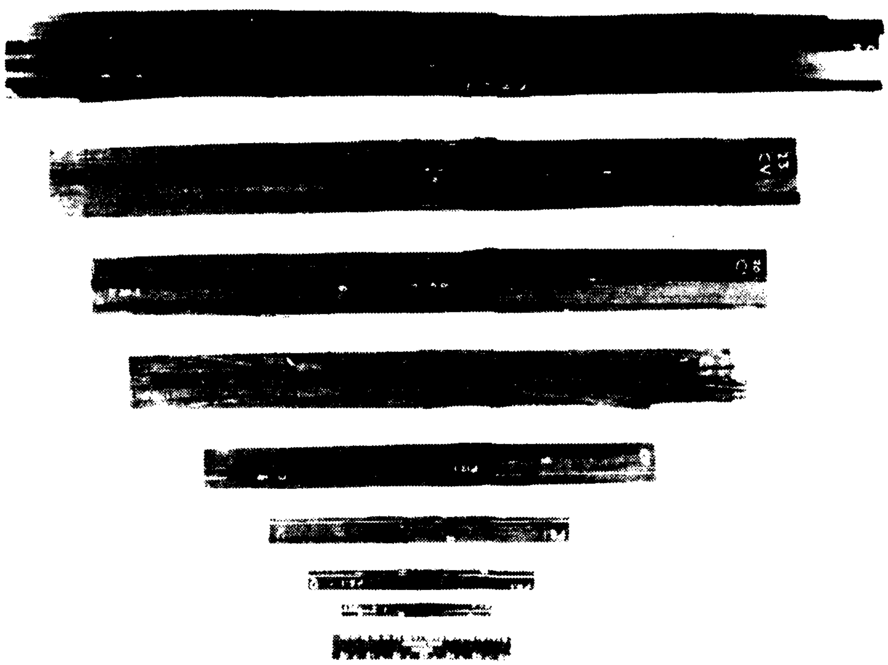


Figure 2. Schematic drawing of the test configuration.

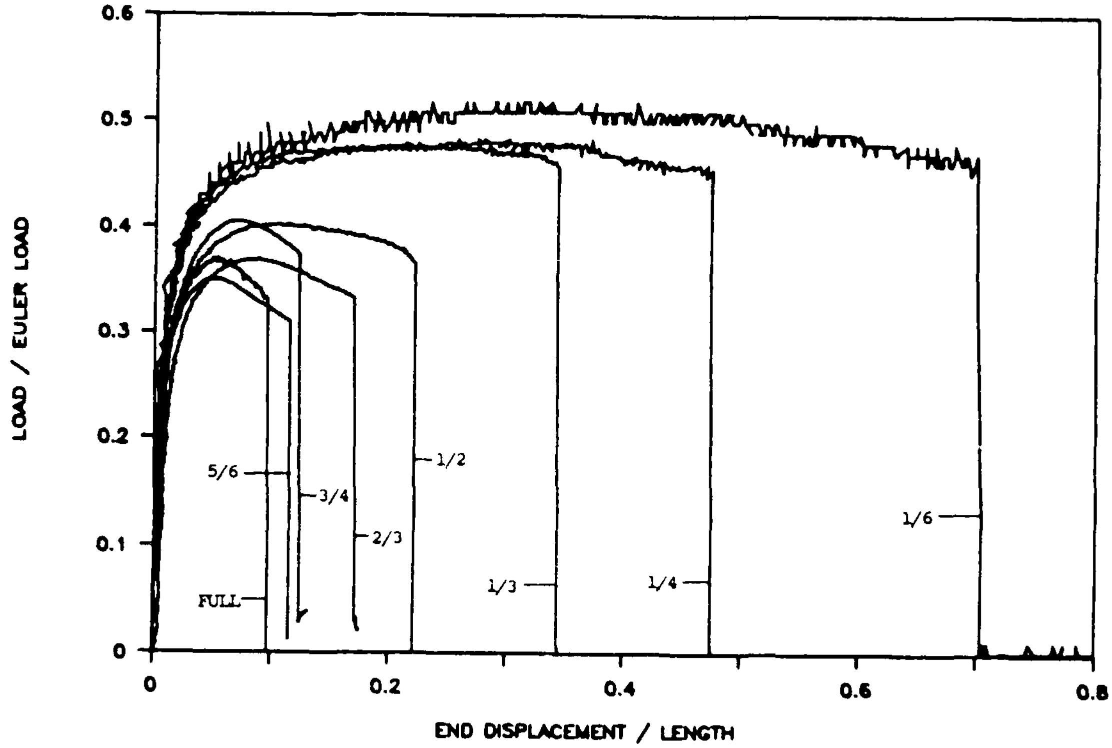


(a) Normalized load versus end displacement.



(b) Failed beam specimens.

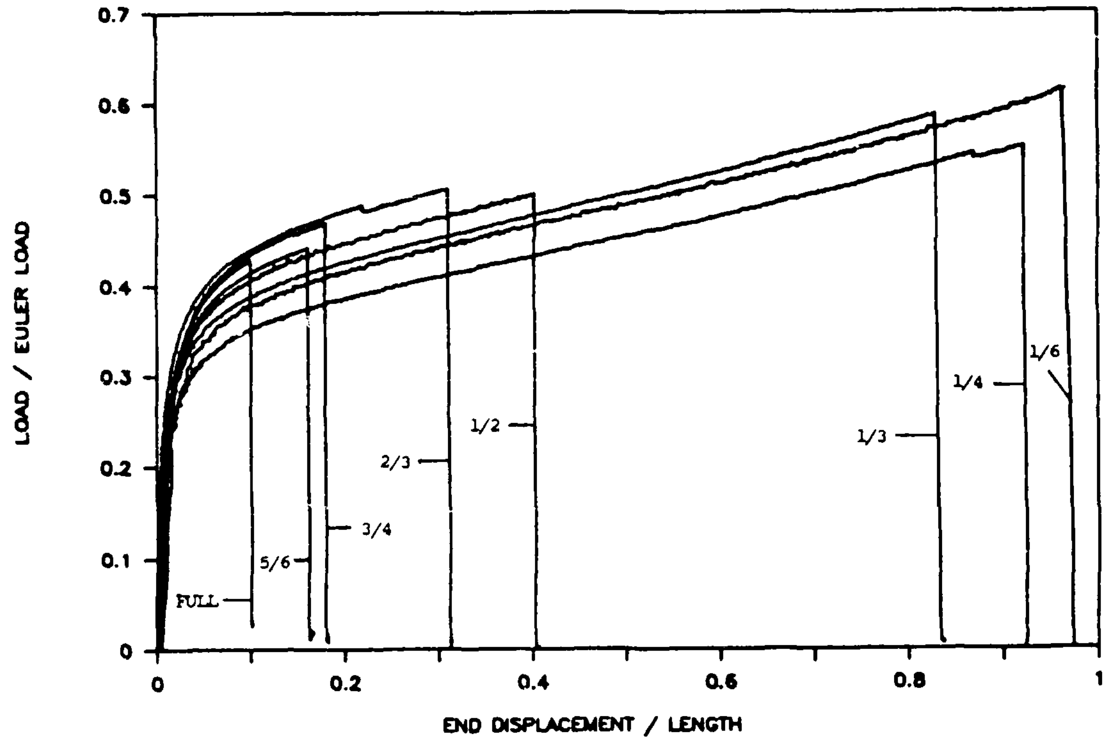
Figure 3. Unidirectional graphite-epoxy composite beam results.



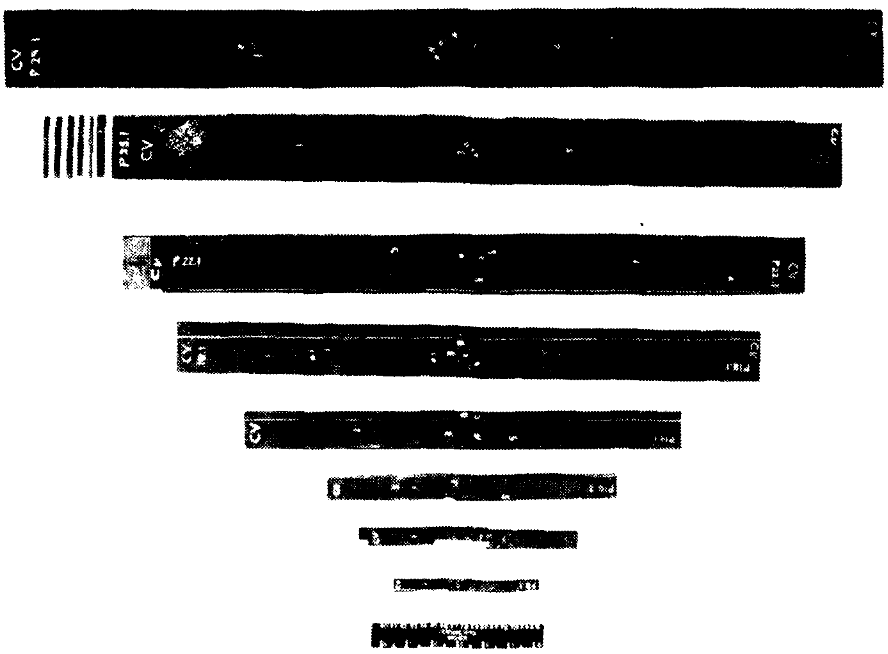
(a) Normalized load versus end displacement.

(b) Failed beam specimens.

Figure 4. Angle ply graphite-epoxy composite beam results.

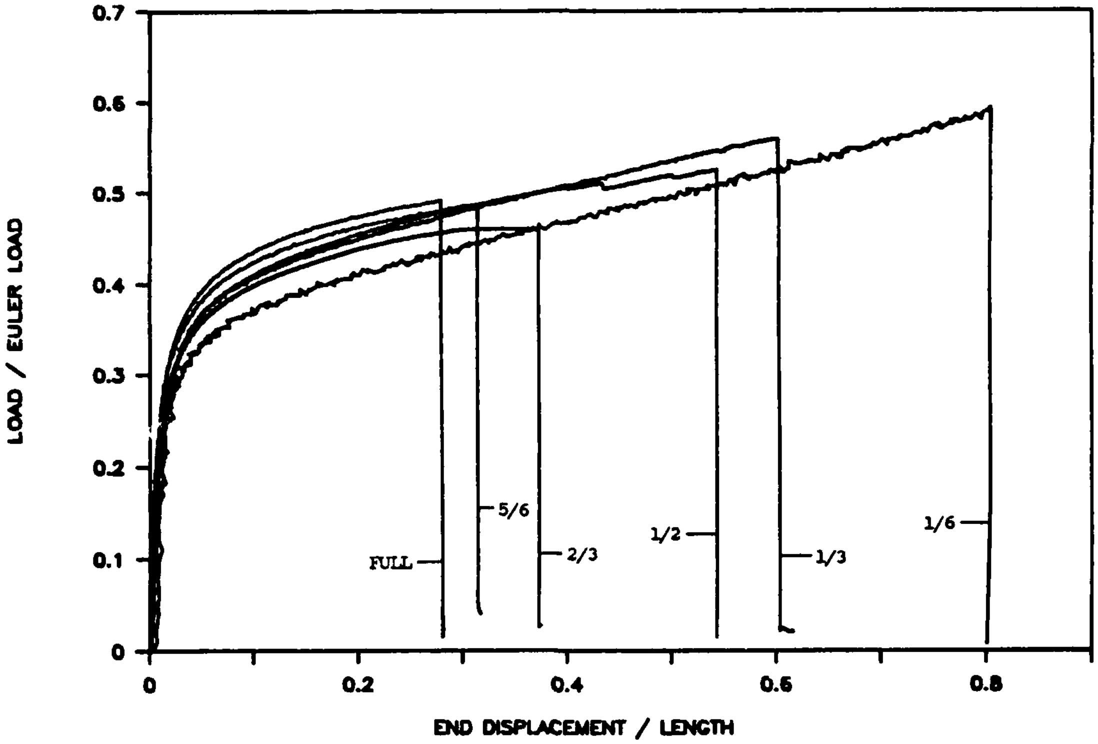


(a) Normalized load versus end displacement.

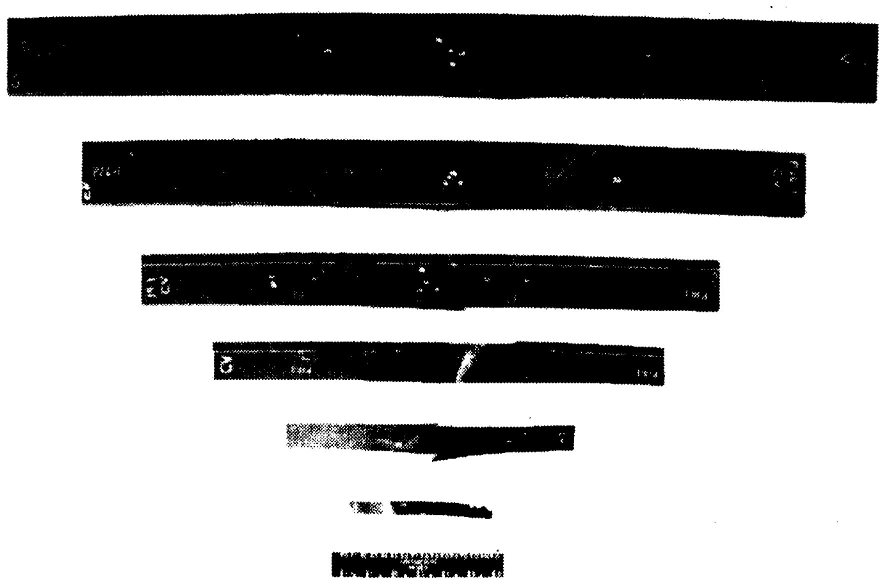


(b) Failed beam specimens.

Figure 5. Cross ply graphite-epoxy composite beam results.

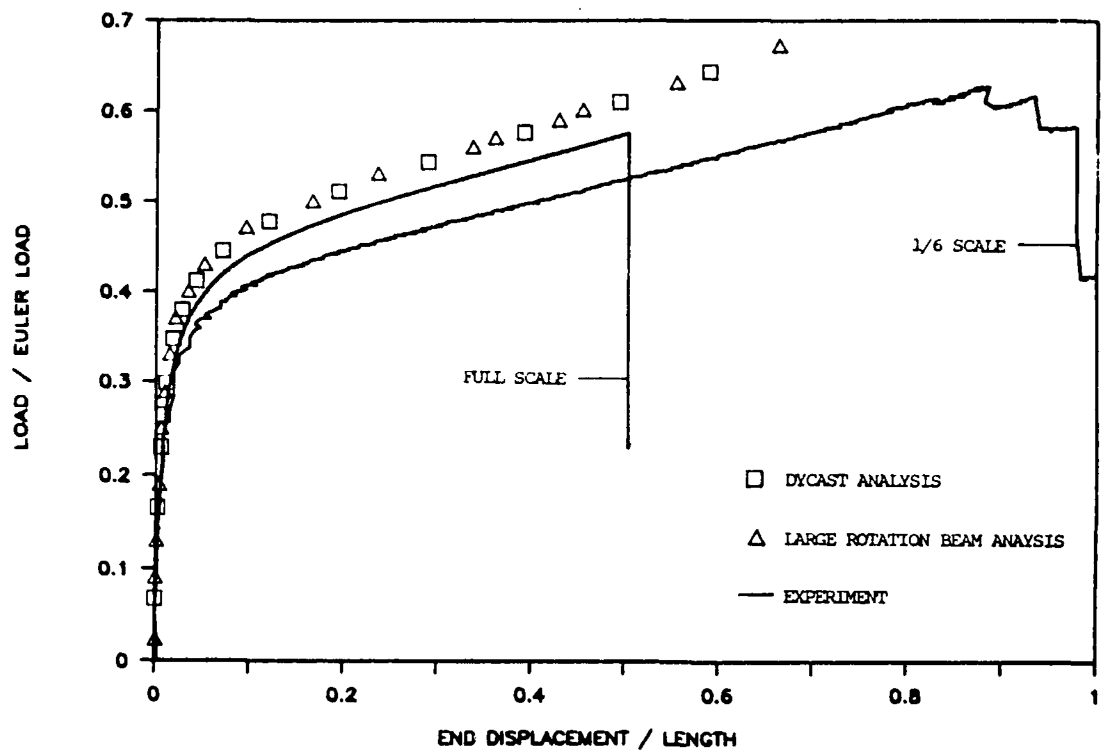


(a) Normalized load versus end displacement.

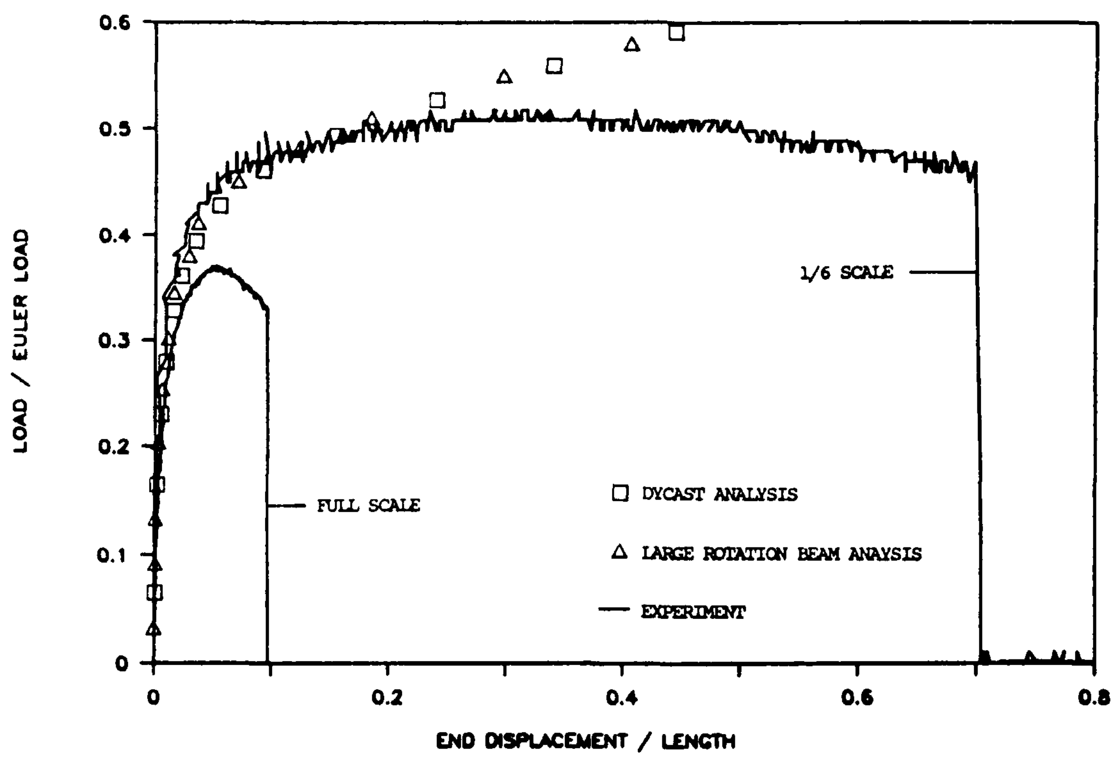


(b) Failed beam specimens.

Figure 6. Quasi-isotropic graphite-epoxy composite beam results.

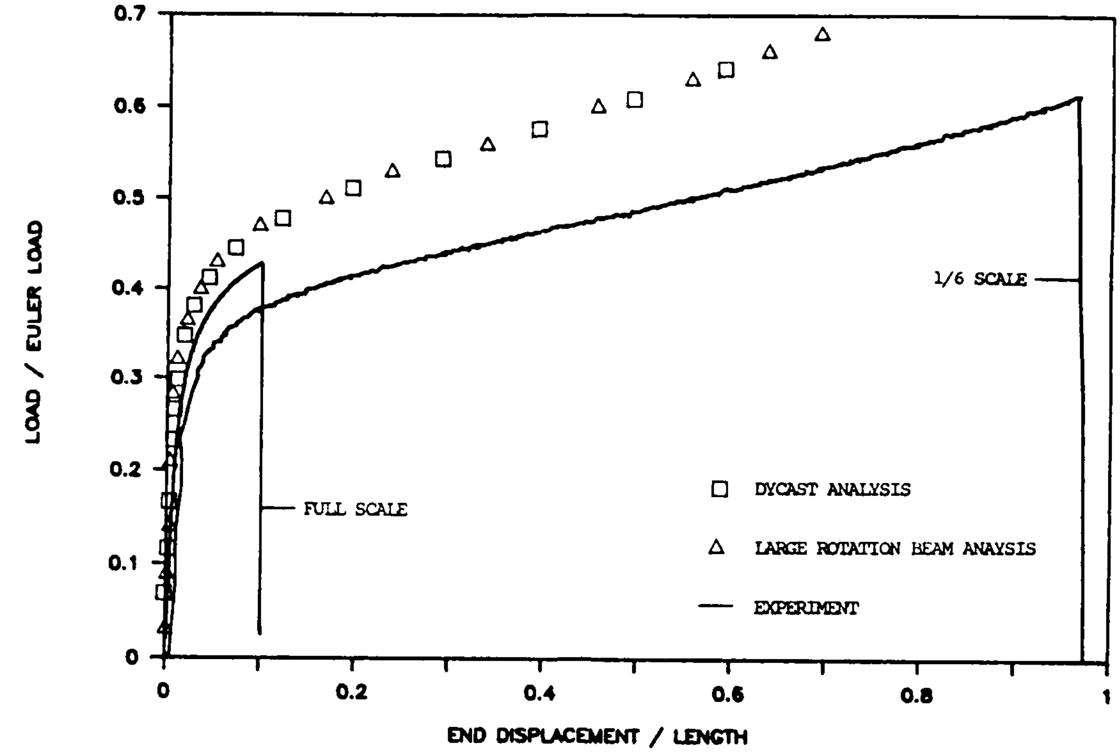


(a) Unidirectional beam results.

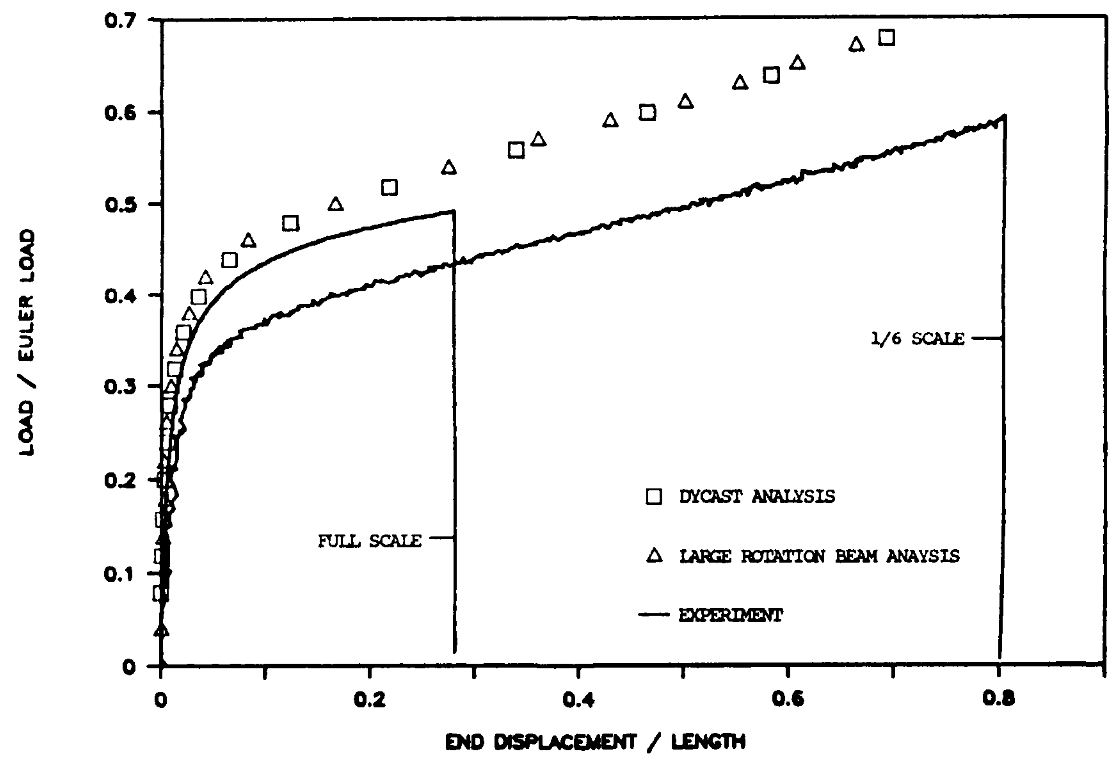


(b) Angle ply beam results.

Figure 7. Comparison of normalized load versus end displacement experimental data for 1/6 and full scale beams with DYCAST finite element analysis and large rotation exact solution.



(c) Cross ply beam results.



(d) Quasi-isotropic beam results.

Figure 7. Comparison of normalized load versus end displacement experimental data for 1/6 and full scale beams with DYCAST finite element analysis and large rotation exact solution.

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